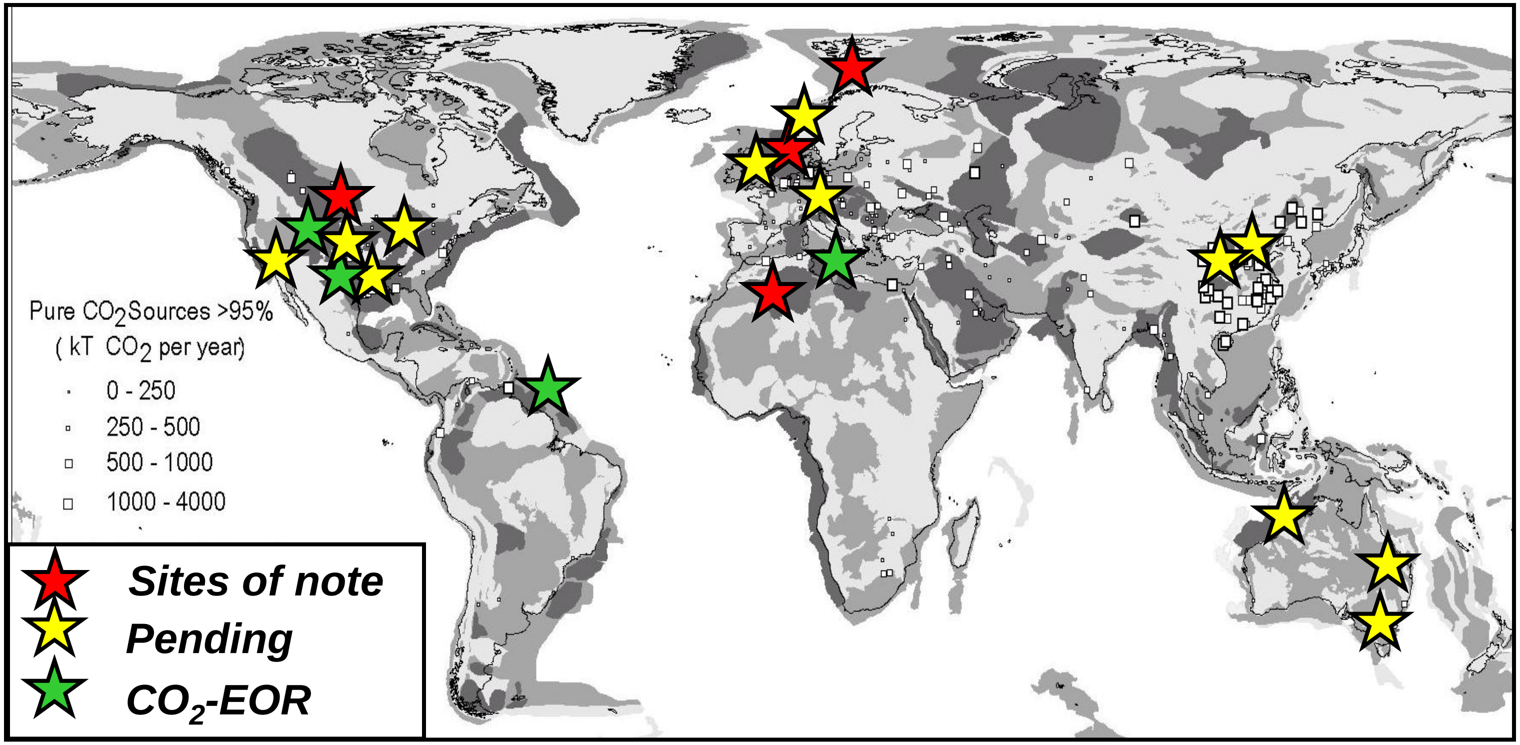
Geological Carbon Sequestration

Assessment for Deployment



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Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO_2 emissions.

Current science and technology gaps appear resolvable at scale

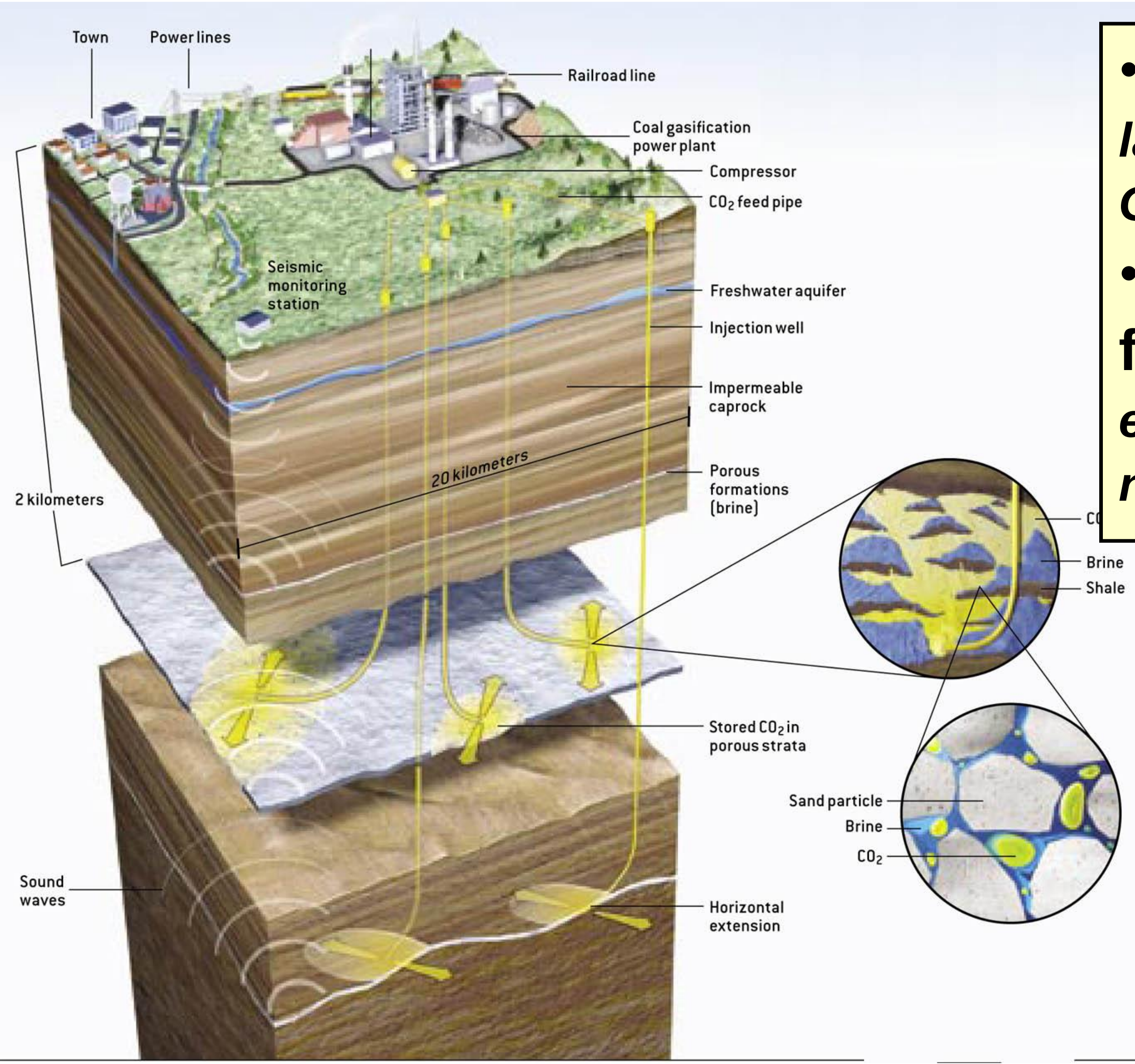
Assessments are needed at national, regional, basin, play, and site levels to understand sequestration resource and key hazards

It appears that China has substantial sequestration resources for large scale deployment

If there's no sequestration resource, there's no project

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

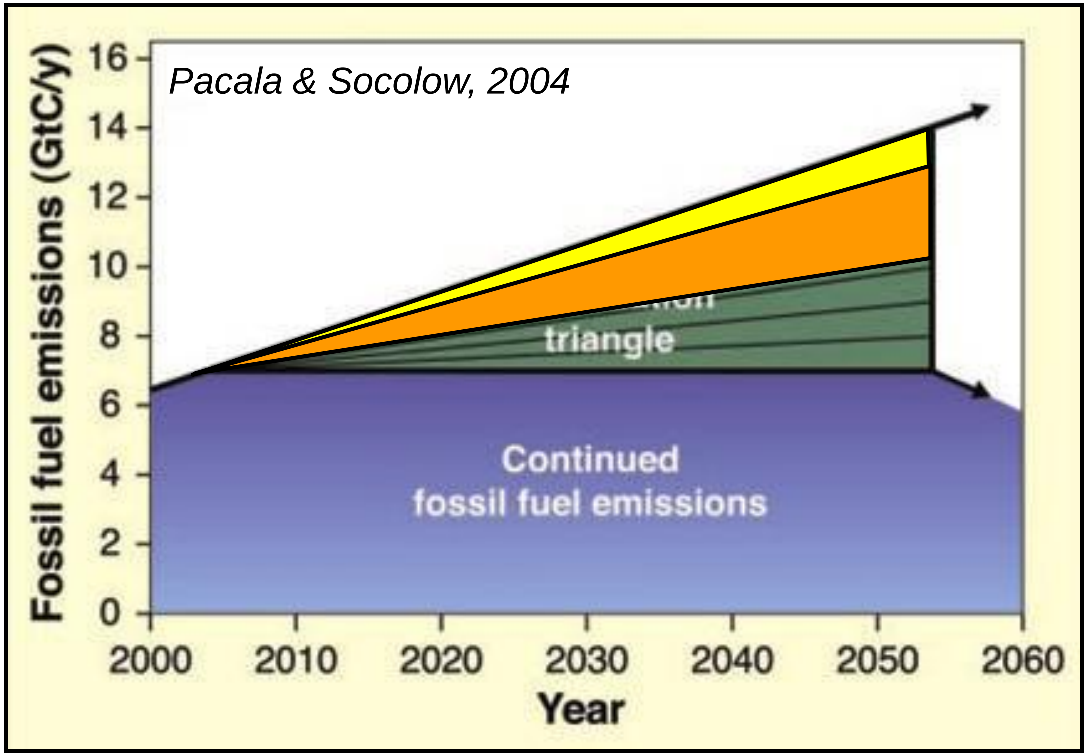
Carbon dioxide can be stored in deep geological formations as a dense, pore-filling fluid



- **Saline Formations:** ***largest capacity (>2200 Gt)***
- **Depleted Oil & Gas fields:** ***potential for enhanced oil and natural gas recovery***

Scientific American, 2005

CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions



Econ. value of 1 wedge ~ $11 T

R. Socolow, 2007

- **A key portfolio component** (w/ cons., effic., nuclear, renew.)
- **Cost competitive to other carbon-free options** (enables others, like hydrogen)
- **Uses proven technology**
- **Applies to existing and new plants**
- **Room for cost reductions (50-80%)**

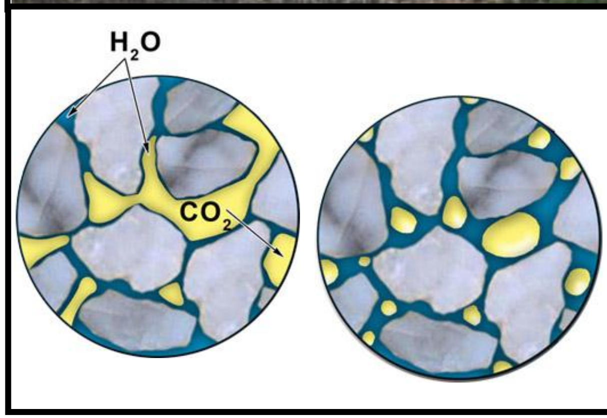
Storage mechanisms are sufficiently well understood to be confident of effectiveness

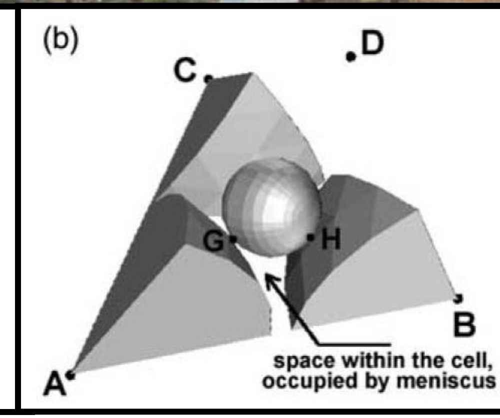
Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

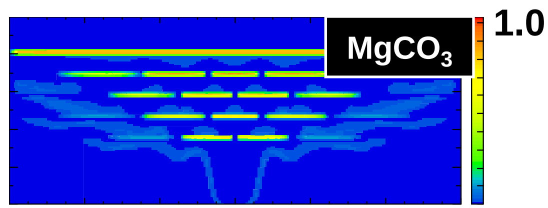
Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

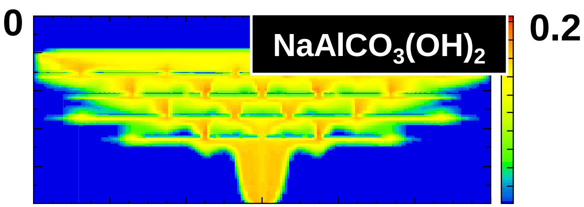
Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)

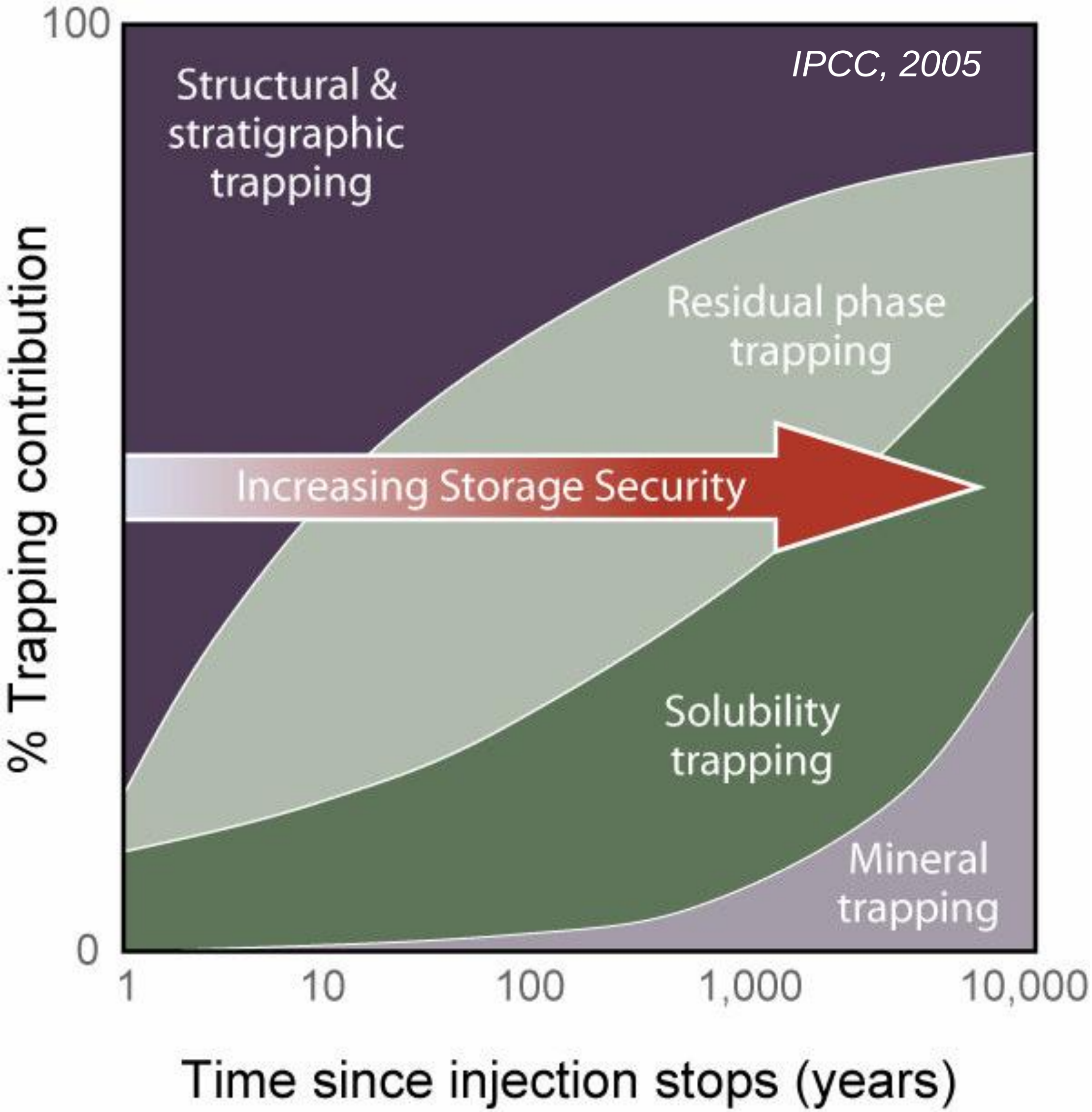








The crust is well configured to trap large CO_2 volumes indefinitely



Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO_2 plumes, trap them residually, & ultimately dissolve them

This means that over time risk decreases and permanence increases

We need large projects to give the technical basis regulation and legal frameworks

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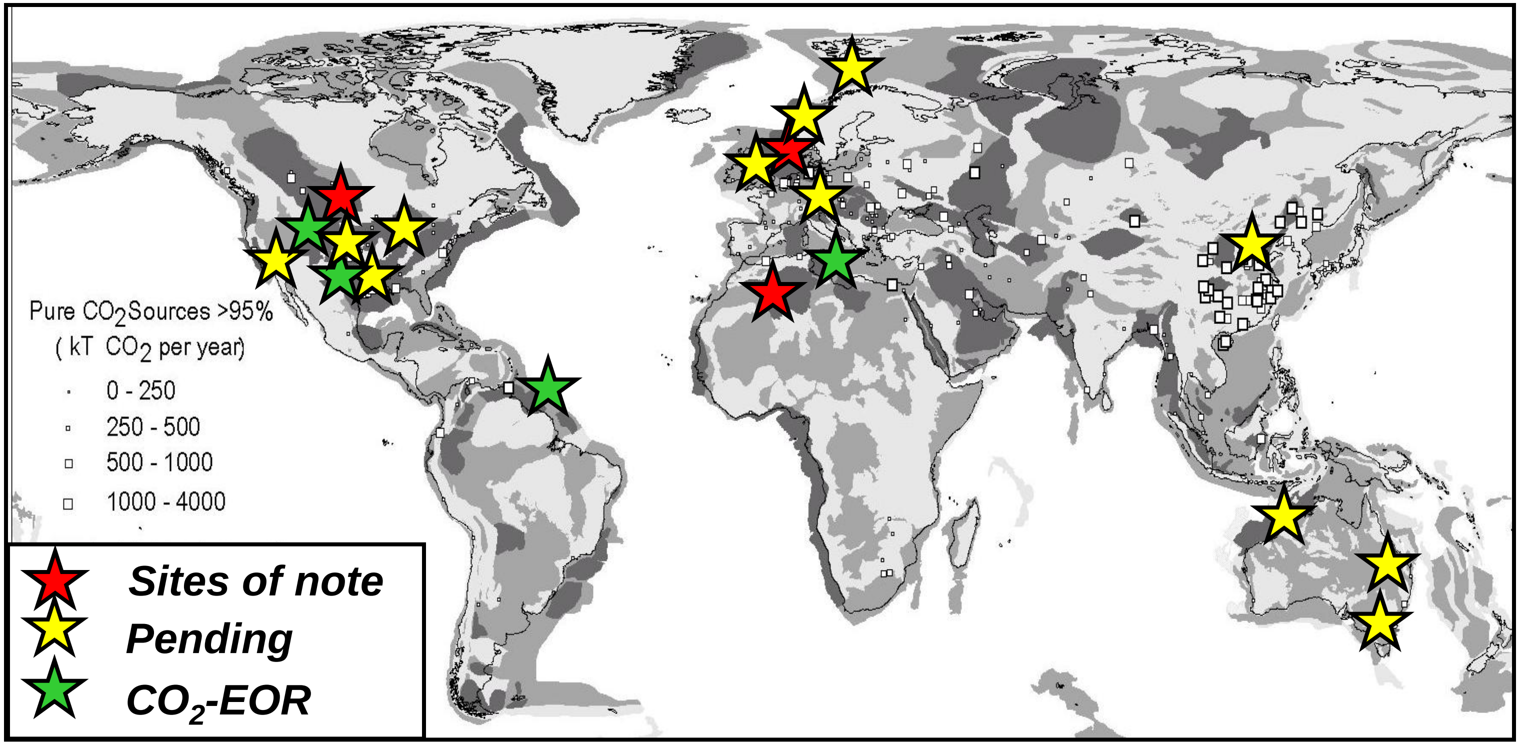
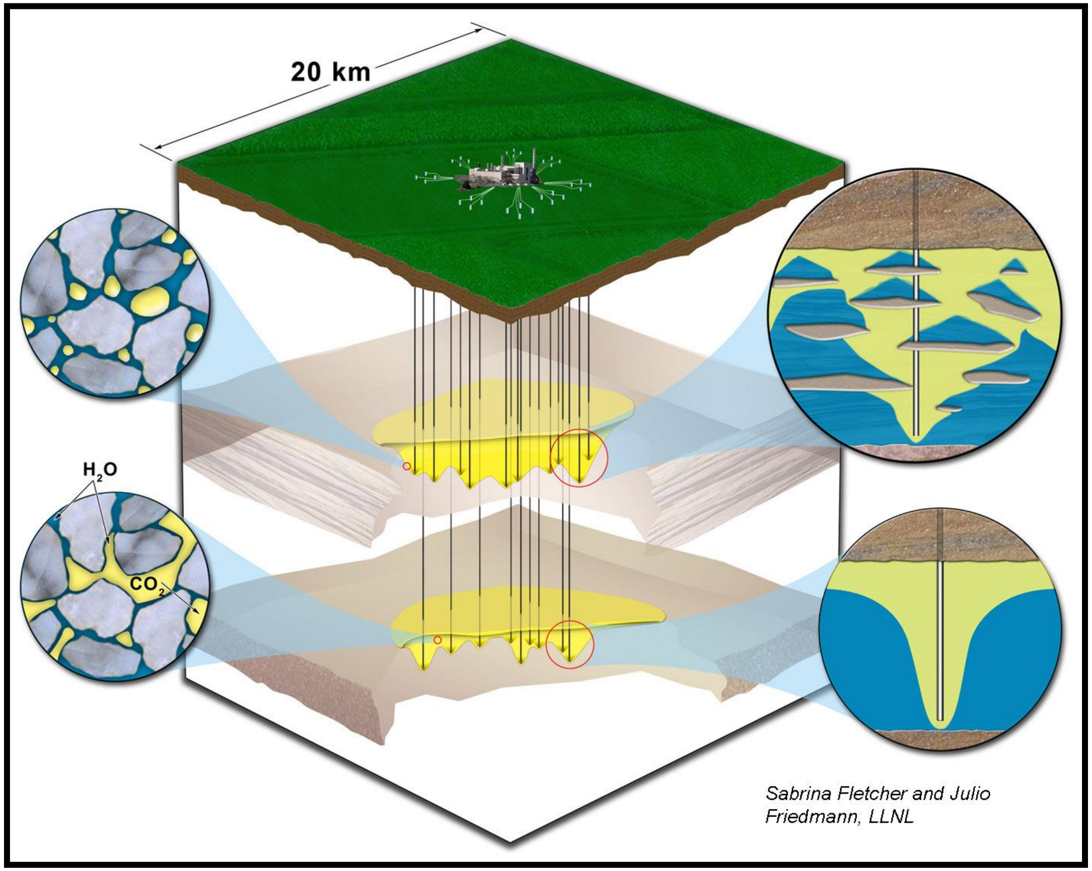
The projects demonstrate the high chance of success for CCS



Large projects must be the CCS engines of discovery

The true scope of large-scale CCS deployment is the primary challenge

Let's suggest that by 2020, all new coal plants will be fitted for CO_2 capture and storage *(watch this space)*. The scope and scale of injection from a single plant must be considered.

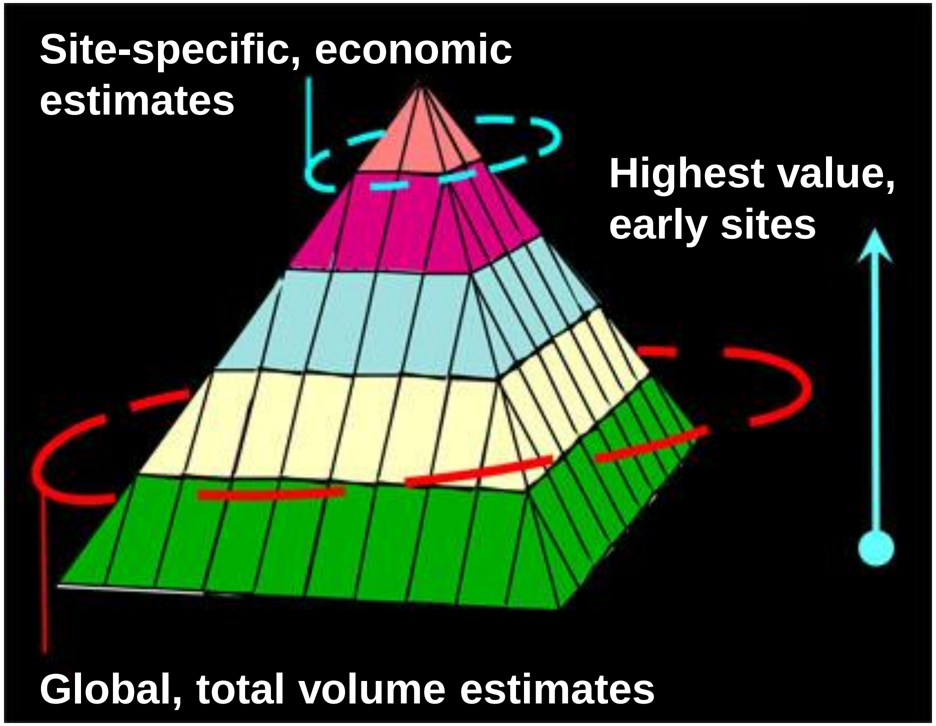


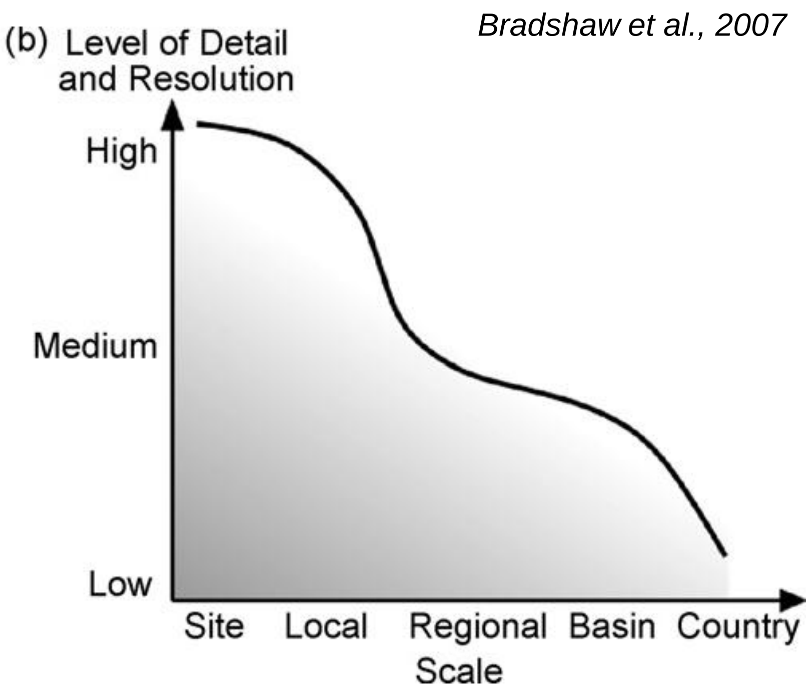
One 1000 MW coal plant, 85% c.f., 90% capture:

- **5-8 MM t CO_2/yr**
- **120,000-200,000 bbl/d (as supercritical phase)**
- **After 60 year, 2.8-4 G bbls**
- **CO_2 plume at 10y, ~10 km radius: at 50 yrs, ~30 km**
- **Many hundreds of wells**
- **Likely injection into many stacked targets**

Sites must receive large volumes of CO_2 at a high rate and contain them for long periods

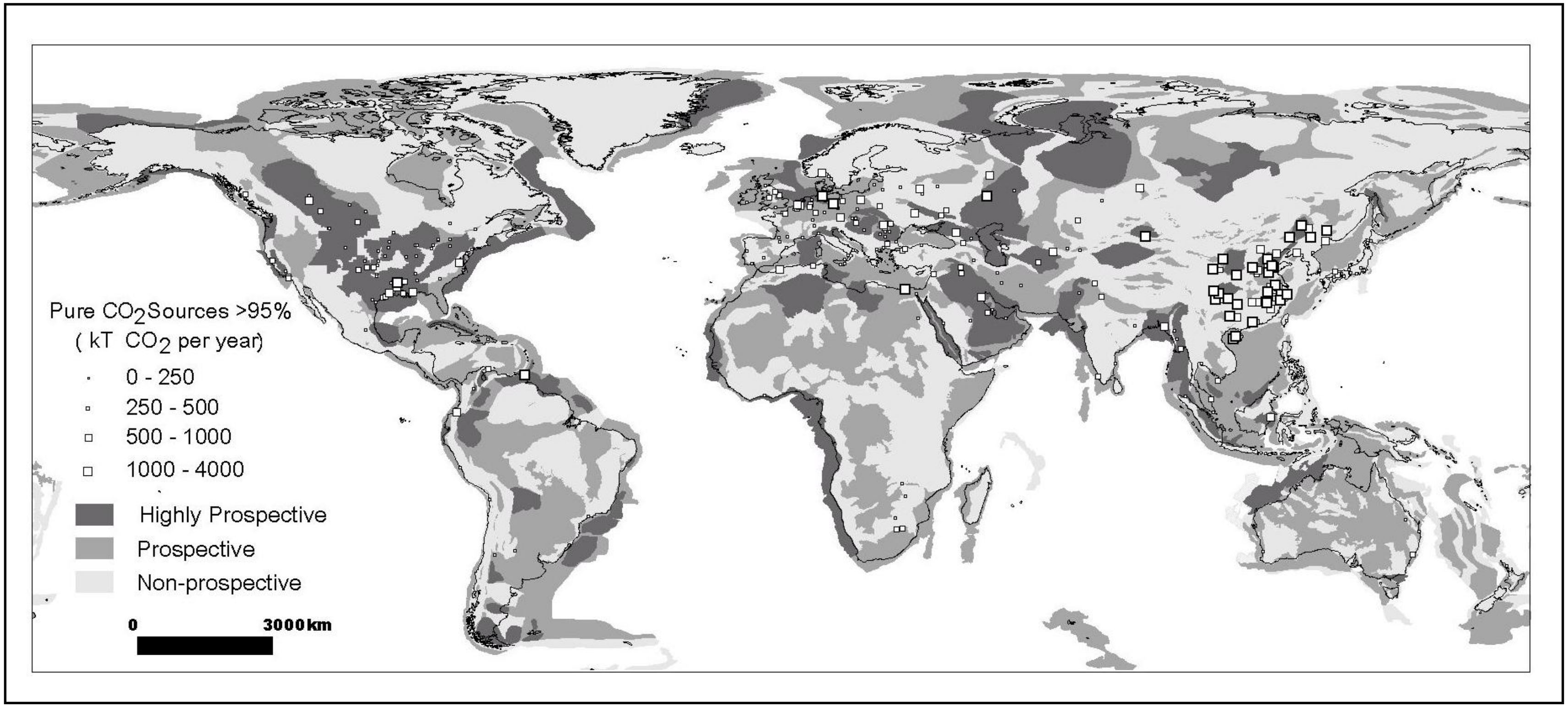
Sequestration resource is like any other natural resource: it must be assessed to be understood





Ultimately, high-quality easy storage will be used first, with lower grade rock volumes used for sequestration through time.

There appears to be enough global storage capacity to sequester >7 Gt CO_2 indefinitely



Bradshaw et al., 2004

- ***More than enough accessible rock volume for sequestration***
- ***Large capacity exists in US, Canada, other OECD countries***
- ***Appears viable in most of world, including India and China***

Australia, Alberta have full assessments
N. America, Europe assessments improving

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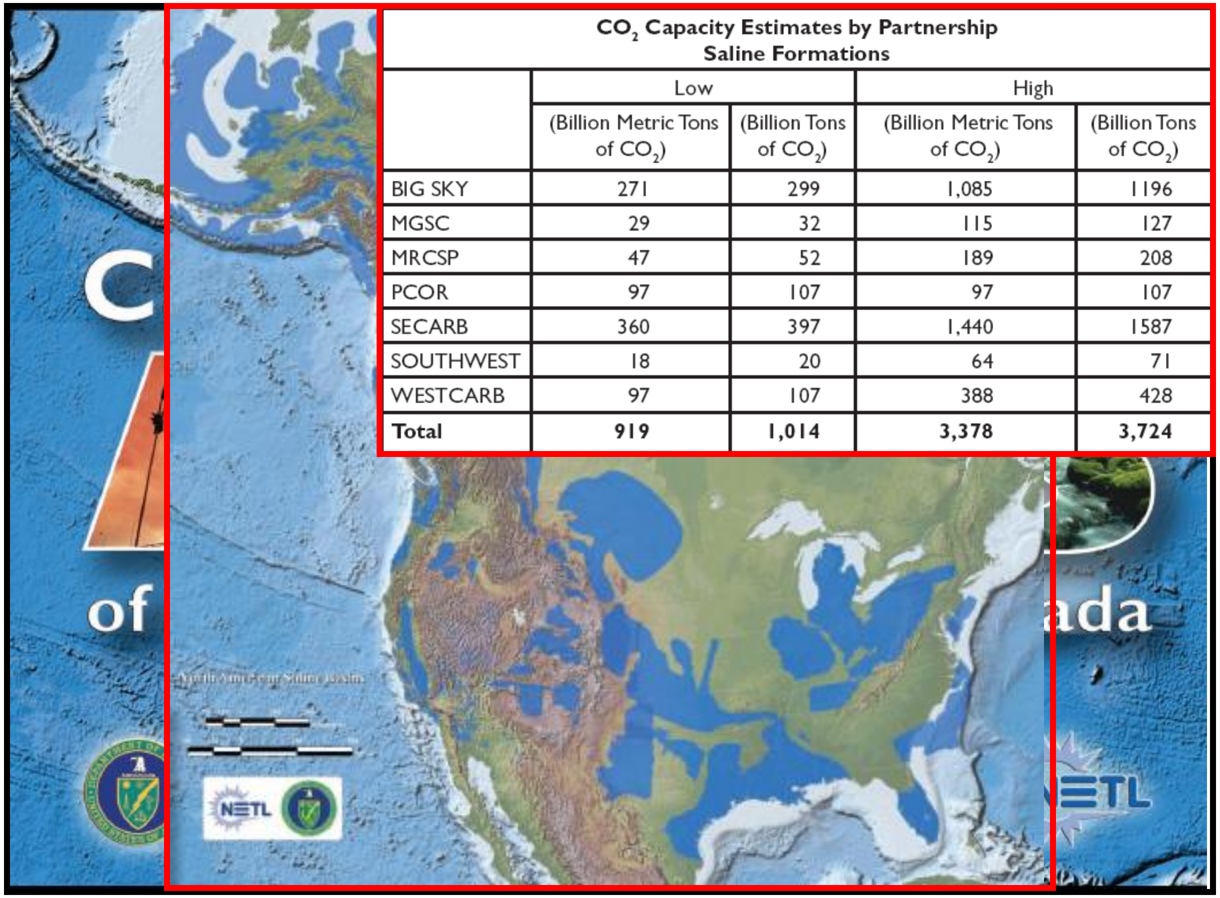

CO_2 Capacity Estimates by Partnership
Saline Formations

	Low		High	
	(Billion Metric Tons of CO_2)	(Billion Tons of CO_2)	(Billion Metric Tons of CO_2)	(Billion Tons of CO_2)
BIG SKY	271	299	1,085	1196
MGSC	29	32	115	127
MRCSP	47	52	189	208
PCOR	97	107	97	107
SECARB	360	397	1,440	1587
SOUTHWEST	18	20	64	71
WESTCARB	97	107	388	428
Total	**919**	**1,014**	**3,378**	**3,724**

http://www.netl.doe.gov/publications/carbon_seq/atlas/index.html

Australia (GEODISC)

- ***$10M, 3 yr work***
- ***Total capacity: 740 Gt***
- ***Risked annual injection rate: ~125 Mt/year***

Alberta

- ***Risked, T gradient calibrated***
- ***4000 Gt (1000 Gt Viking Fm.)***

US/N. America

- ***Total Capacity: 1200-3500 Gt***
- ***Some formation level assessments***
- ***Regional partnership work proceeding***

Total capacity estimates are less useful that injection rate estimates
Resource density estimates broadly absent

Almost all current capacity estimates are poor: this is a high priority issue!

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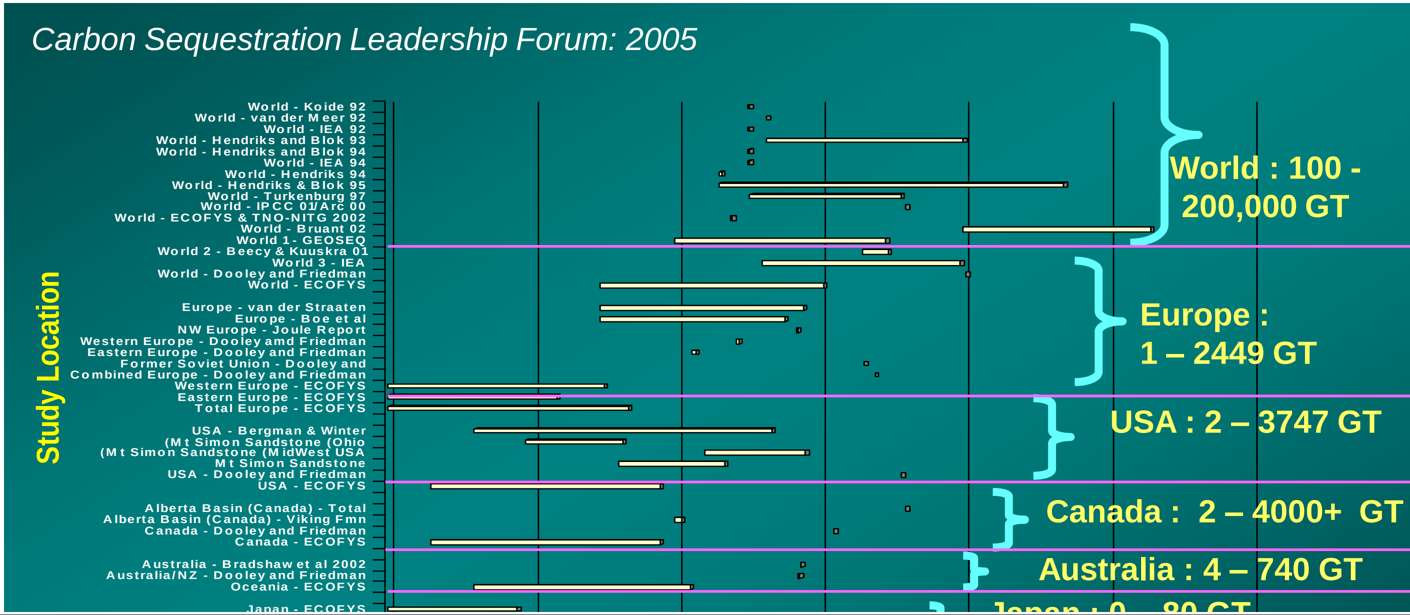


Table 1 – Applicability of current methodologies for estimating CO_2 storage capacity to various assessment scales and storage mechanisms

Storage mechanism	Trapping mechanism	Temporal nature[a]	Coefficients needed[b]	Assessment scale				
				Country	Basin	Regional	Local	Site specific
Oil and gas reservoirs	Stratigraphic and structural	No	Yes	✓	✓	✓	✓	✓
	Enhanced oil recovery	No	Yes	–	–	–	✓	✓
Coal beds	Adsorption	No	Yes	✓	✓	✓	✓	✓
Deep saline aquifers	Stratigraphic and structural	No	Yes	✓	✓	✓	✓	✓
	Residual gas	Yes	?	–	–	–	✓	✓
	Solubility	Yes	Yes	–	–	–	✓	✓
	Mineral precipitation	Yes	Yes	–	–	–	✓	✓
	Hydrodynamic	Yes	Yes	–	–	–	✓	✓

Bachu et al., 2007

Site selection due diligence requires characterization & validation of ICE

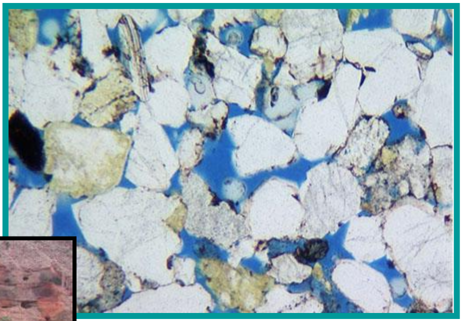
Injectivity ***Capacity*** ***Effectiveness***

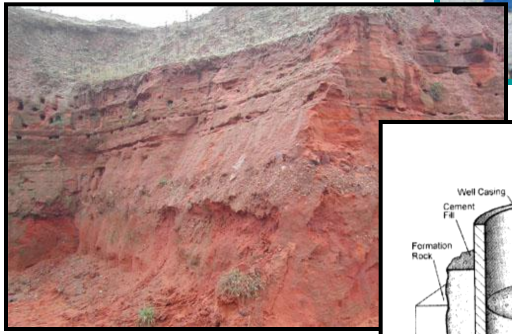
Injectivity
- **Rate of volume injection**
- **Must be sustainable (months – years)**

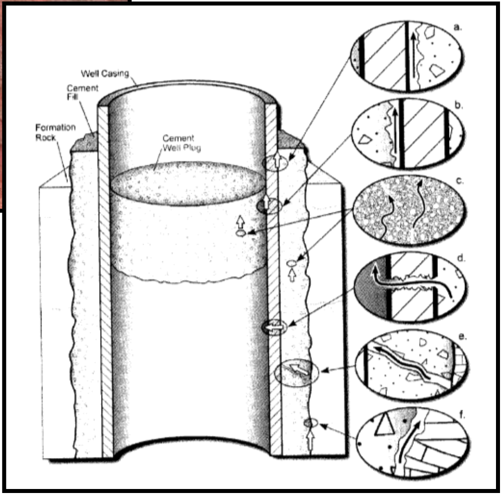
Capacity
- **Bulk (integrated) property**
- **Total volume estimate**
- **Sensitive to process**

Effectiveness
- **Ability for a site to store CO_2**
- **Long beyond the lifetime of the project**
- **Most difficult to define or defend**

No sequestration resource = no project







Gasda et. al, 2005

A lot of conventional (and new) technology exists to characterize ICE

Injectivity

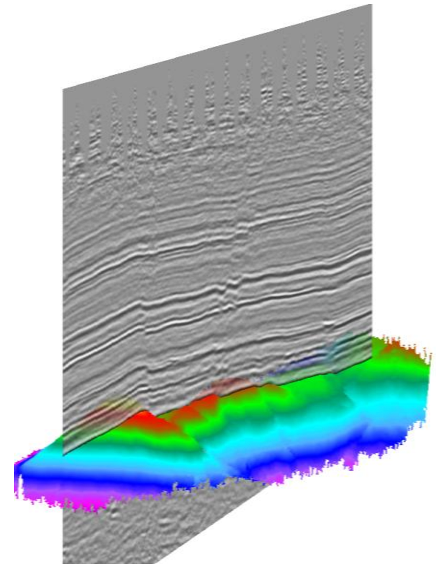
- Pump/injection tests
- Conventional P&P analyses
- Conventional reservoir mapping
- Fm. parting pressure tests

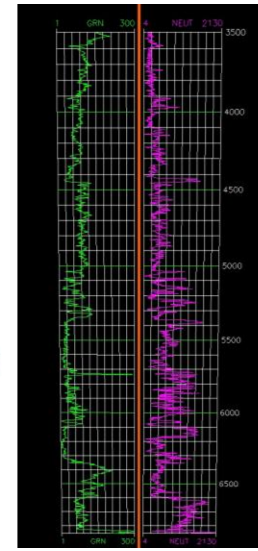
Capacity

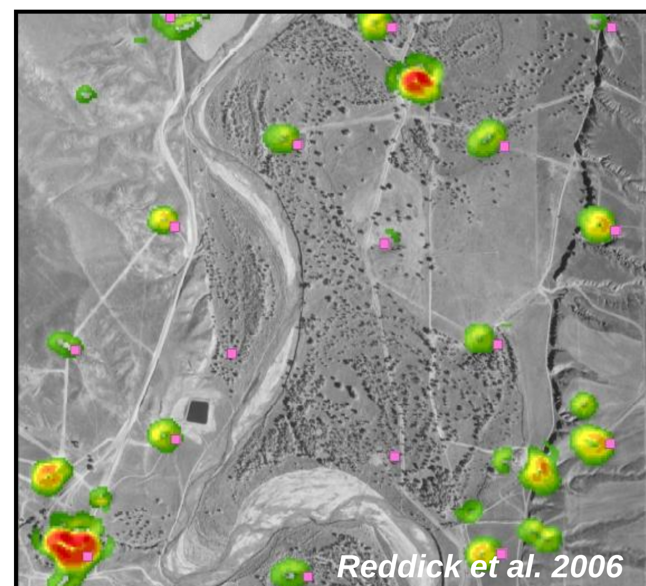
- Conventional reservoir mapping
- Residual phase core measurement
- Conventional simulation or RTM

Effectiveness

- Orphaned/abandoned well detection
- Conventional geological mapping
- Geomechanical analyses
- Capillary entry pressure tests

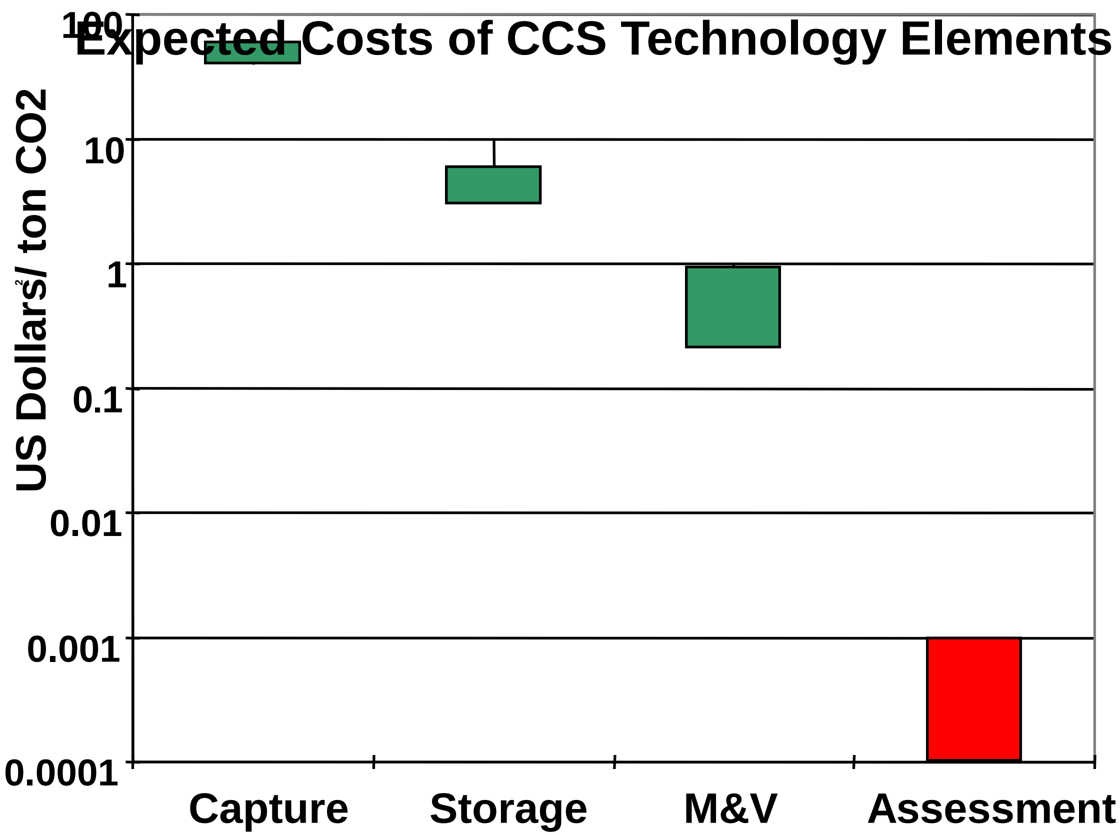






Reddick et al. 2006

Assessments represent the lowest cost, highest impact step in CCS



Friedmann et al., 2006

Capture: \$40-80/t CO_2
Storage: \$3-8/t CO_2
M&V: \$0.2-\$1.0/t CO_2
Assessment: <\$0.01/t CO_2

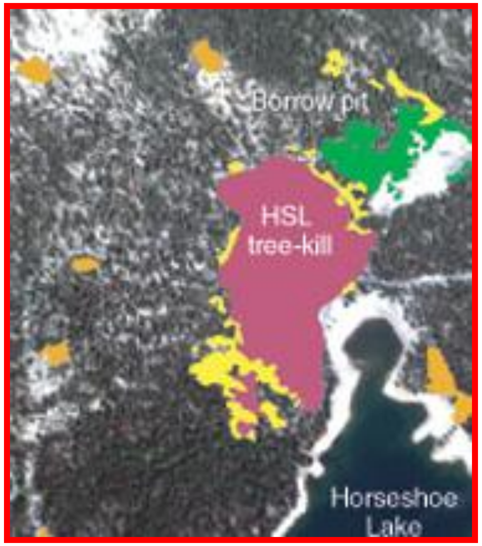
IN GENERAL TERMS, CCS **is cost competitive with new nuclear and wind.**

Locally, this will vary considerably

For any large injection volume, local assessment is extremely low in cost and can be executed with conventional technology

Leakage risks remain a primary concern and should be focus of assessments

1) High CO_2 concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Economic risks flow from uncertainty in subsurface, liability, and regulations



Elements of risk can be prioritized

- Understanding high-permeability conduits (wells and faults)
- Predicting high-impact effects (asphyxiation, water poisoning)

The focus for CO_2 storage operations should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

RISK = Probability * consequence

RISKS are often difficult to determine

- **Hard to get probability or consequence from first principles**
- **Current dearth of large, well-studied projects prevents empirical constraint**

Because of local nature of hazards, prioritization (triage) is possible for any case

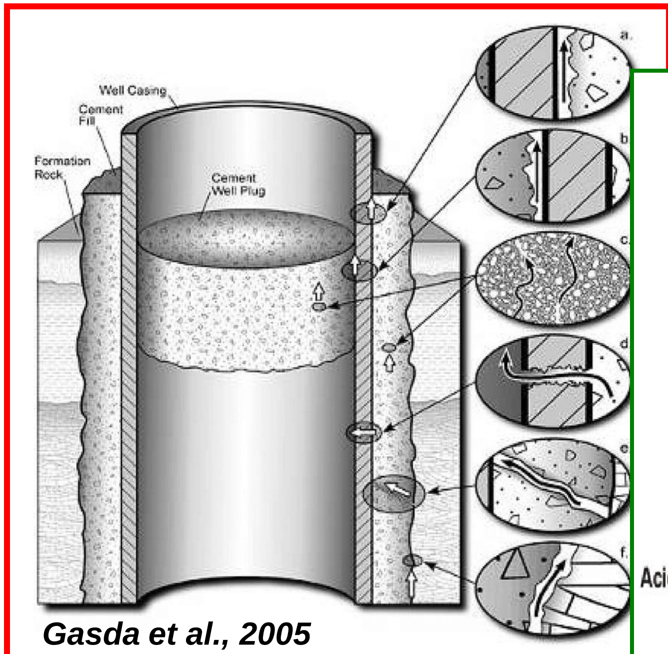
Hypothetical Case: Texas GOM coast

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

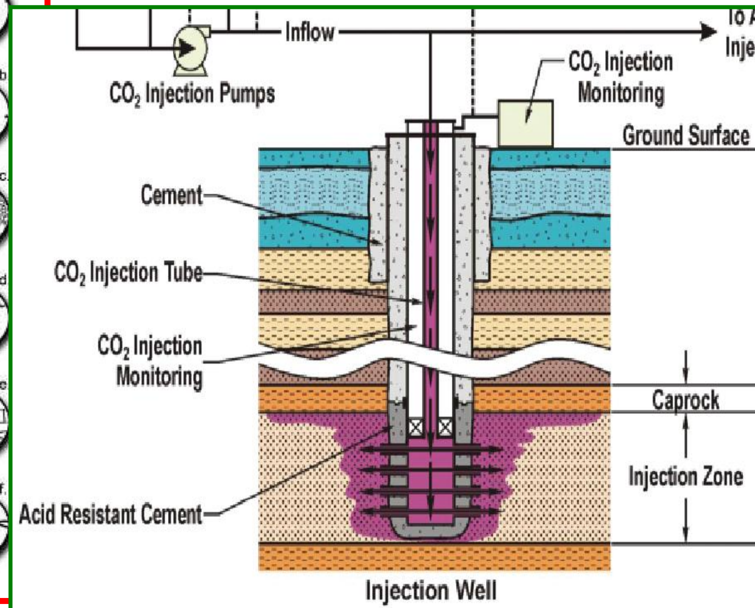
Wells are main hazard to site integrity: assessments are critical to success

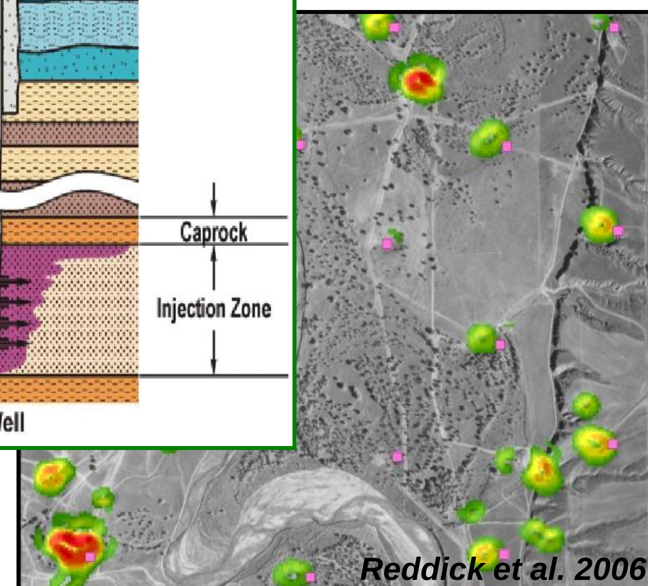
We have some understanding of well failure modes



Gasda et al., 2005

We can properly design CO_2 wells and plug failed wells



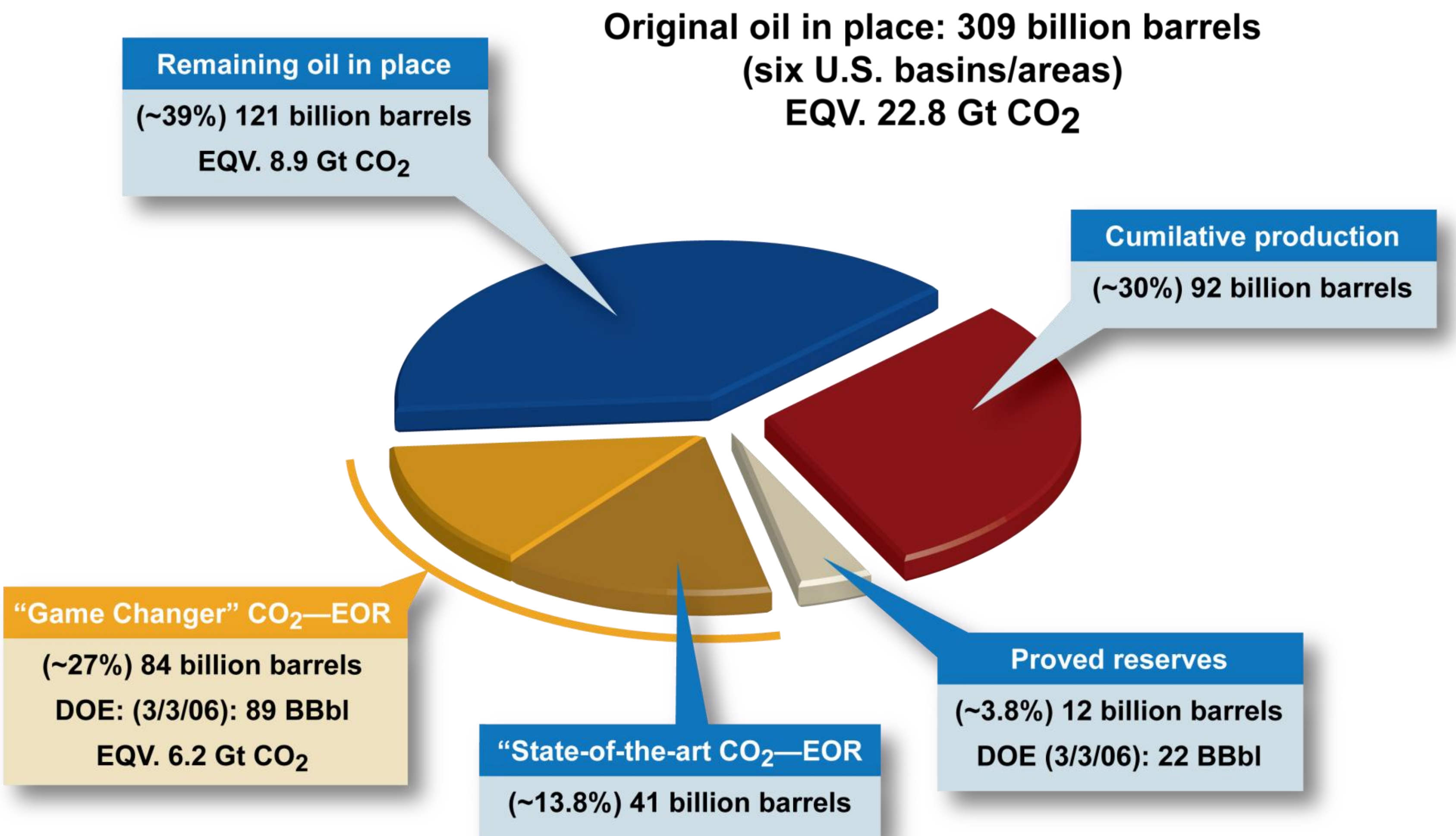


Reddick et al. 2006

We can identify and recomplete lost wells

Managing and maintaining well integrity is important to avoiding failure and risk minimization

Available CO_2 will dramatically increase U.S. oil production before going into permanent "storage"



EQV. Equivalent volume

Advanced Resources International, 2005

China capacity & opportunities can be quickly assessed and pursued

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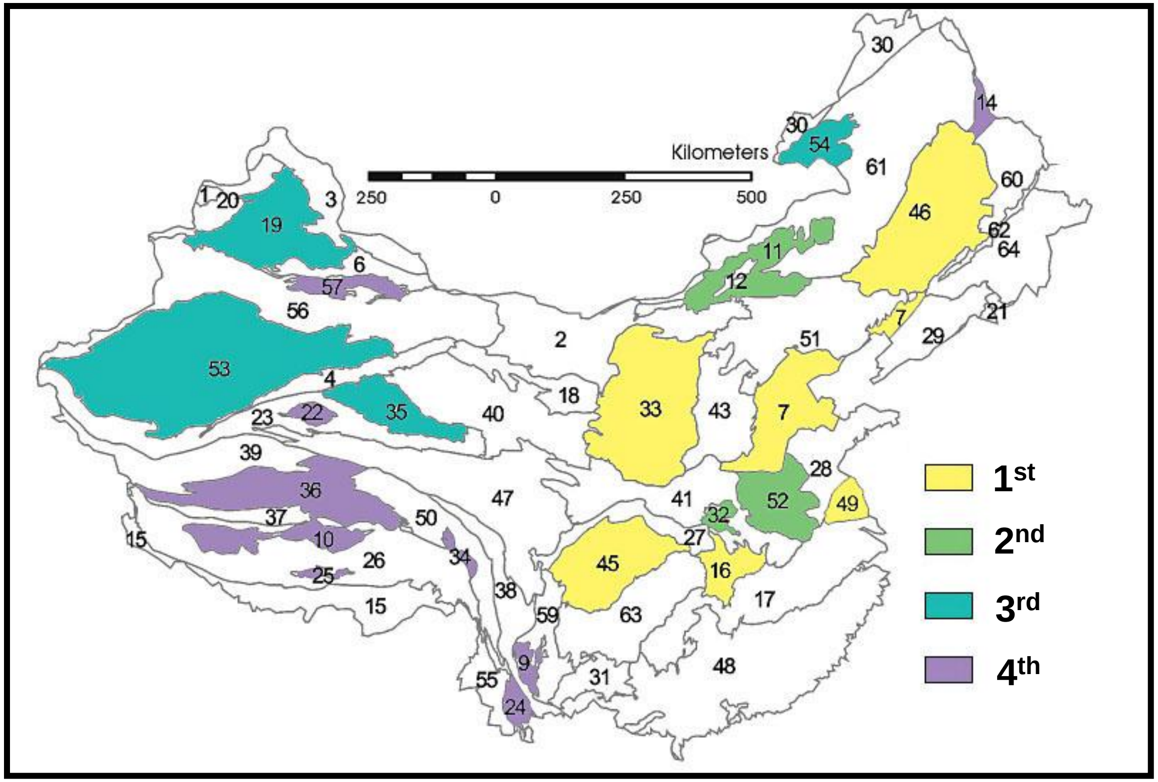


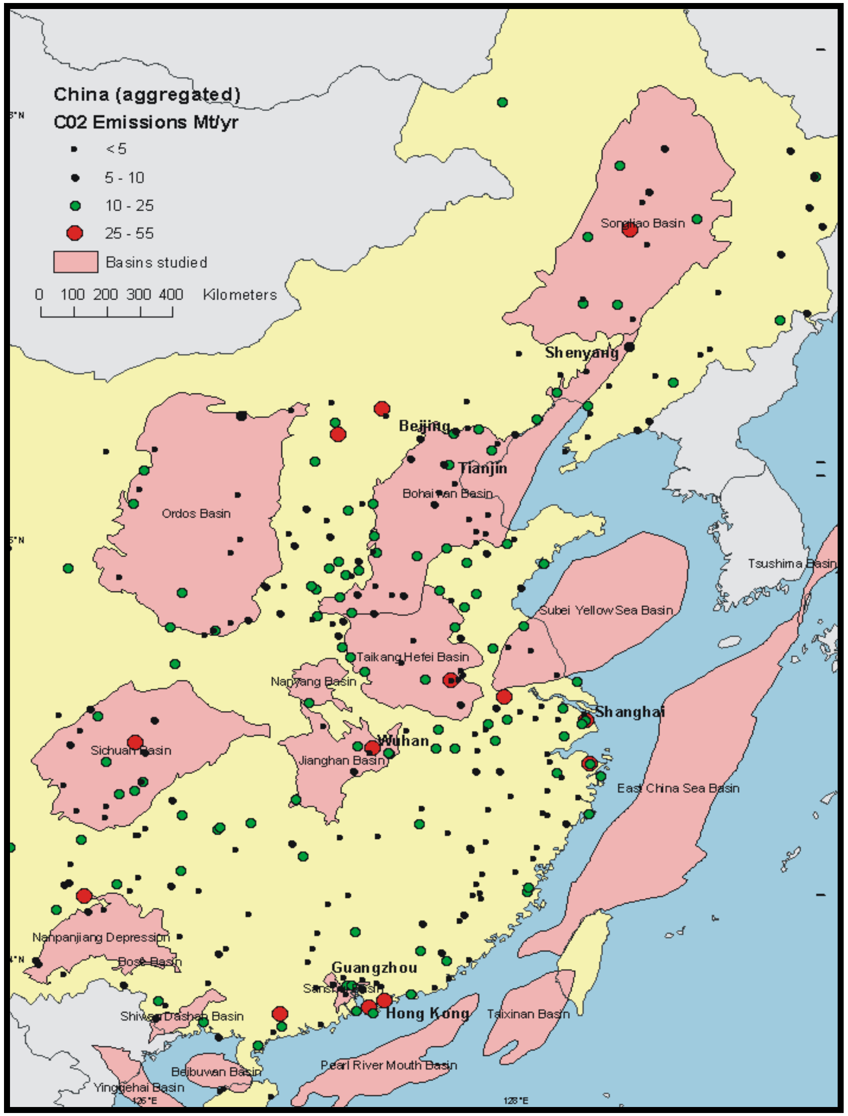
These basins lie near large, concentrated CO_2 sources and contain a relevant range of geology. Assessments, short pipelines, and wells could be completed at low cost.

China is geologically very complex, requiring a long, large-scale effort at capacity assessment.

However, only a few of basins matter the most due to source proximity. These could be assessed fairly quickly and easily given proper cooperation and data access

- **Songliao**
- **Bohainan-Liaodong**
- **Sichuan**
- **Jianghan**
- **Ordos**
- **Subei**

The six main basins show multiple prospective targets, high density of point sources



Newlands & Langford., 2005

Basin-scale assessments should rank onshore targets in key basins

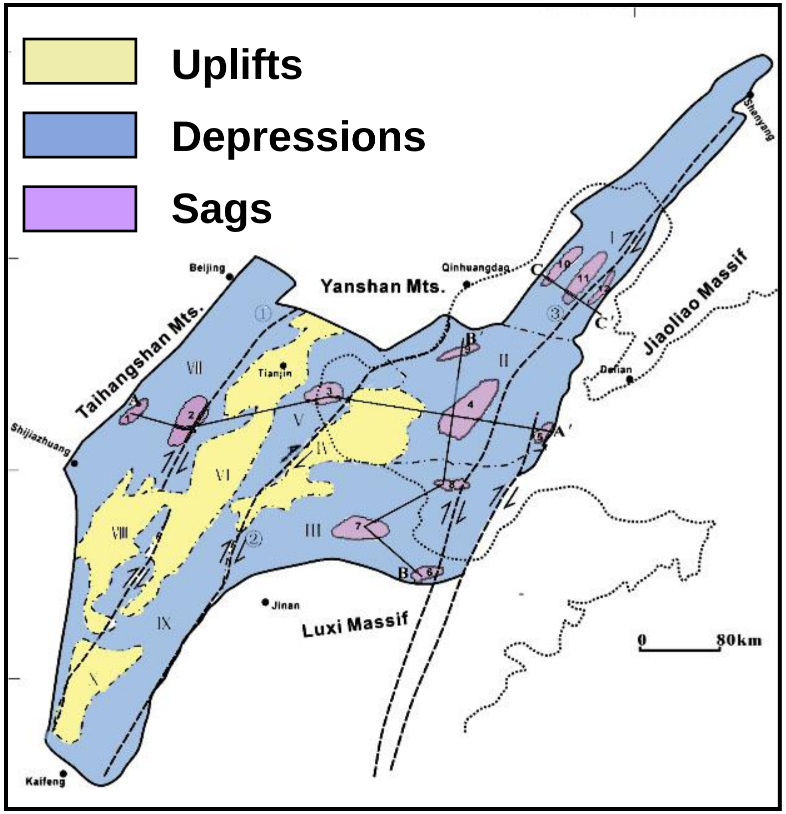
- ***Data rich (85% of production)***
- ***Most EOR opportunities***
- ***Low drilling costs***

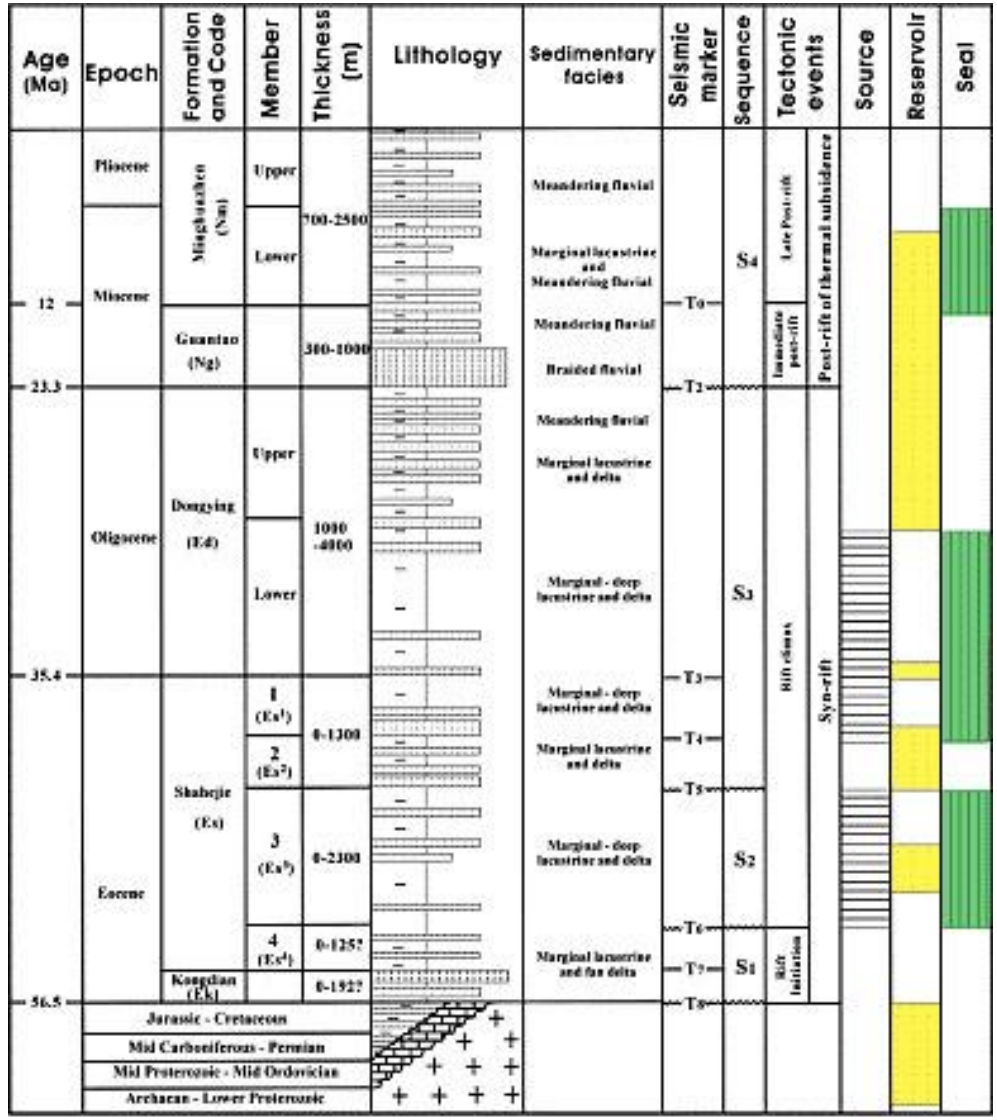
Songliao, Bohai, and Subei all show high prospectivity and underlie significant point sources

High likelihood of successful CO_2-EOR: some begun

Joint effort between Geoscience Australia and RIPED: assessment of 10 eastern basins

Bohai is a particularly good early target, with good targets near Beijing and Tianjin





Sedimentary depressions and sags have largest thicknesses of reservoir/seal pairs; uplifts have good EOR opportunities

Yang & Xu, 2004

CO_2 storage in the Ordos basin provides unique opportunities and challenges

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Many target reservoirs

- Majiagou Fm. (Ord. carbonates)
- Taiyuan Fm. (Carb. sandstones)
- Xiashihenzi Fm. (Perm. sandstones)
- Yanchange Fm (Jurassic sandstones)

Low permeability in general

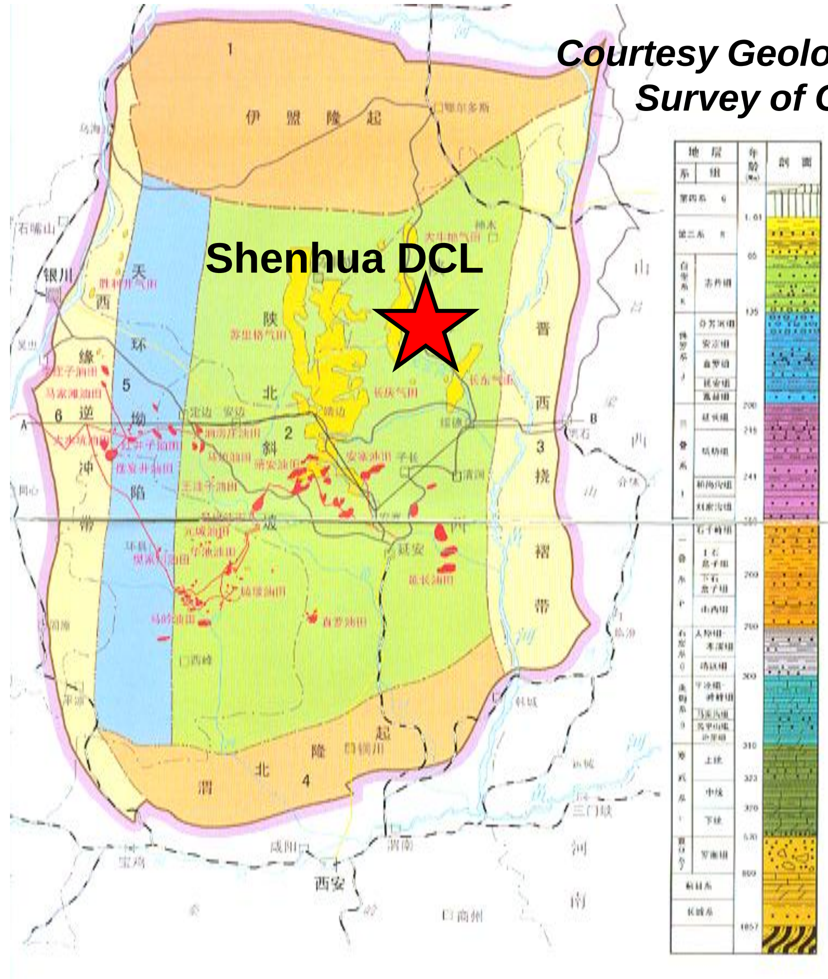
- Must characterize injectivity carefully
- Can be augmented (deviated wells)
- Improved residual phase trapping
- Many stacked potential targets

Structural complexity modest

- Compression and extension
- Not isotropic in-situ stress

Demonstrated effectiveness

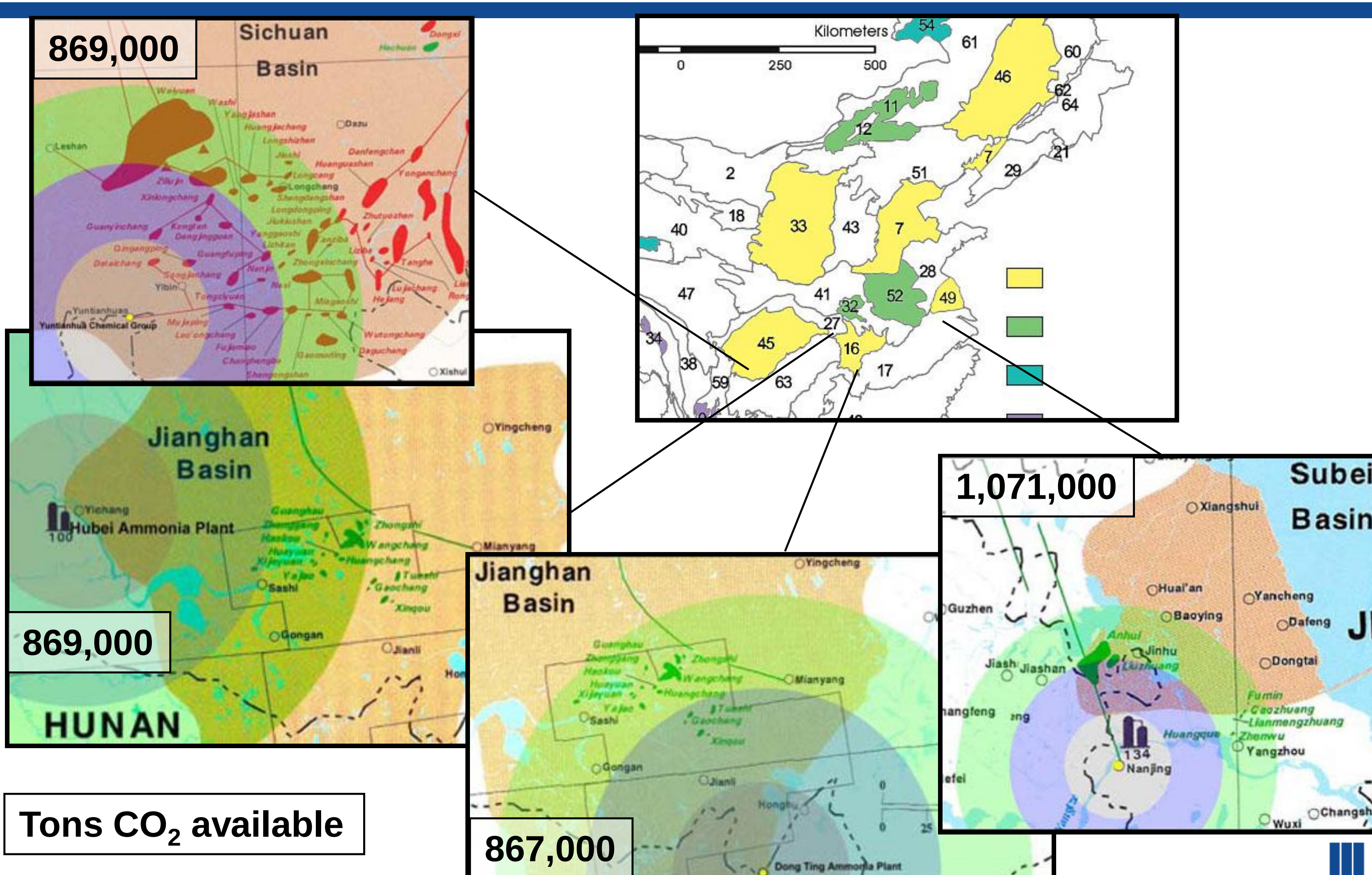
- Substantial oil & gas seals (>5MPa capillary entry pressures)



Courtesy Geological Survey of China

New project: Shenhua DCL, West Virginia U., DOE-FE, LLNL

Low-cost, value-added targets in Eastern China would help demonstrate effectiveness quickly



Meng et al., 2005

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